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The long-term and interannual variability of summer fresh water storage over the eastern Siberian shelf: Implication for climatic change

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[1] A time series of summer fresh water content anomalies (FWCA) over the Laptev and East Siberian sea shelves was constructed from historical hydrographic records for the period from 1920 to 2005. Results from a multiple regression between FCWA and various atmospheric and oceanic indices show that the fresh water content on the shelves is mainly controlled by atmospheric vorticity on quasi-decadal timescales. When the vorticity of the atmosphere on the shelves is antycyclonic, approximately 500 km^3 of fresh water migrates from the eastern Siberian shelf to the Arctic Ocean through the northeastern Laptev Sea. When the vorticity of the atmosphere is cyclonic, this fresh water remains on the southern Laptev and East Siberian sea shelves. This FWCA represents approximately 35% of the total fresh water inflow provided by river discharge and local sea-ice melt, and is about ten times larger than the standard deviation of the Lena River summer long-term mean discharge. However, the large interannual and spatial variability in the fresh water content of the shelves, as well as the spatial coverage of the hydrographic data, makes it difficult to detect the long-term tendency of fresh water storage associated with climate change.

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1. Introduction

[2] The eastern Siberian shelf can be regarded as an integrator of recent Arctic climatic changes that have occurred over the Eurasian Arctic and surrounding land. These include the reduction in sea-ice extent and thickness [*Comiso*, 2002; *Laxon et al.*, 2003; *Rigor and Wallace*, 2004; *Stroeve et al.*, 2005], warming of atmosphere [*Comiso*, 2003], and increase of river discharge [*Peterson et al.*, 2002]. Overall, these changes result in profound modification of the local oceanic freshwater cycle [*Peterson et al.*, 2006; *Serreze et al.*, 2006]. As a main source of the fresh water of the Arctic Ocean, the Siberian shelf is also critically important for feeding the halocline layer that buffers the cold, fresh surface layer from the warmer, saltier Atlantic water beneath [*Aagaard et al.*, 1981; *Rudels et al.*, 1996].

[3] The eastern Siberian shelf, consisting of the Laptev and East Siberian seas, is controlled by Siberian river discharge, ice formation and melting, brine rejection in coastal polynyas, and exchange with the Arctic Ocean and adjoining seas. It is also generally believed to be sensitive to changes in atmospheric wind-forcing [see, e.g., *Shpaikher et al.*, 1972; *Johnson and Polyakov*, 2001; *Steele and Ermold*, 2004; *Dmitrenko et al.*, 2005]. A close relationship between the surface layer freshwater content and atmospheric circulation was first suggested by *Shpaikher et al.* [1972]. In particular, *Shpaikher et al.* showed that in 1956, cyclonic atmospheric circulation in the Laptev Sea region led to eastward diversion of Lena River water and a negative salinity anomaly east of the Lena Delta. In 1961, anticyclonic vorticity resulted in negative salinity anomalies northward from the Lena Delta associated with northward transport of freshwater, and a corresponding salinity increase eastward of the delta. Moreover, drifter observations in summer 1995 (a year with anticyclonic atmospheric circulation) showed distinct water transport from the East Siberian Sea toward the west [*Münchow et al.*, 1999]. The distribution of river discharge inferred from tracer data also shows cross-shelf offshore transport of river water from the Laptev Sea during the "anticyclonic" summers of 1995–1996 while an along-shore eastward transport was observed during the summer of 1993, a year with cyclonic circulation [*Guay et al.*, 2001]. *Steele and Ermold* [2004] describe the relationship between decadal surface salinity anomalies on the Siberian shelf in terms of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices. Finally, *Dmitrenko et al.* [2005] found that variability of summer surface salinity over the Laptev and East Siberian shelves is mainly attributable to the difference in local wind patterns associated with positive and negative phases of atmospheric vorticity over the adjacent Arctic Ocean.

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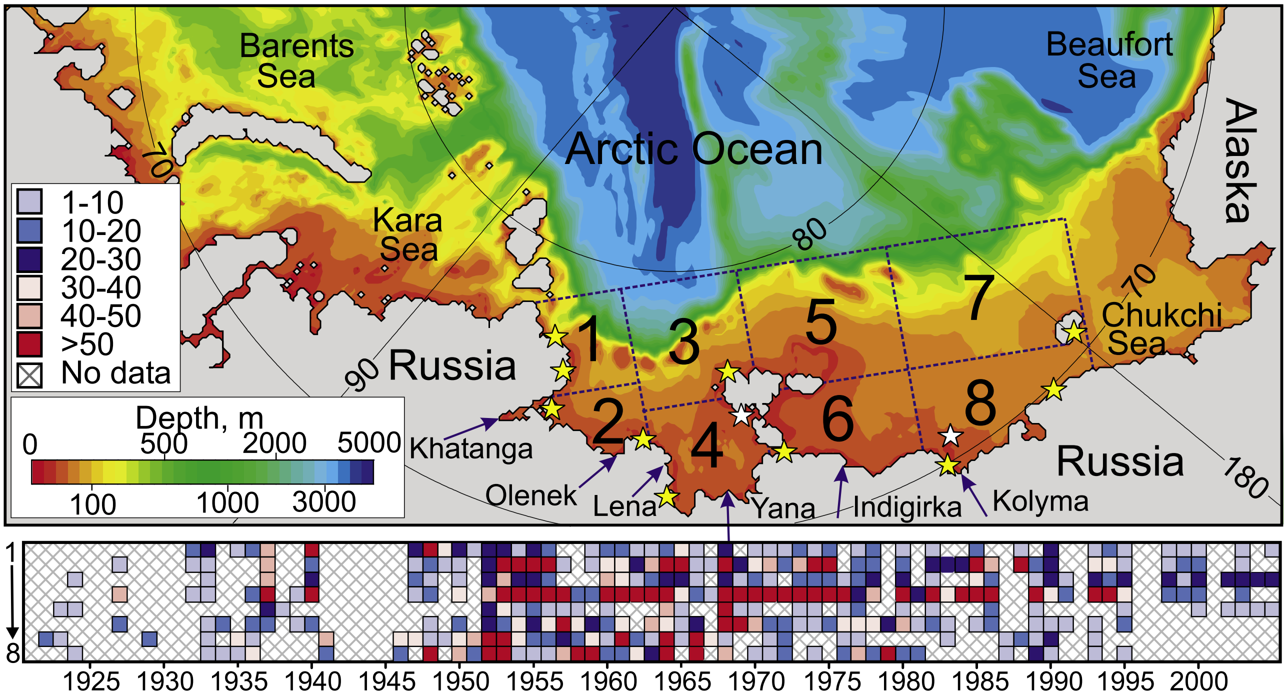

Figure 1. Map of the eastern Arctic Ocean. Dashed lines show sub-regions of the Laptev (1–4) and East Siberian (5–8) seas. The number of summer stations occupied between 1920 and 2005 within sub-regions 1–8 is shown in the bottom panel. The locations of regional SAT and fast ice thickness observations are shown by yellow and white stars, respectively. Rivers with runoff exceeding 20 km^3/summer (May–September) are shown by the blue arrows. Bottom topography was derived from the International Bathymetric Chart of the Arctic Ocean.

[4] The variability and long-term tendency of the fresh water content (FWC) over the Eurasian shelf and the fraction of the total FWC variability that is attributable to atmospheric forcing and climate change, however, remain unclear. *Steele and Ermold* [2004] report a freshening of the White Sea and salinification of the surface water layer in the eastern Siberian shelf. *Simstich et al.* [2005] demonstrated that the increase in runoff fraction of the Kara Sea during the second half of the 1990s was the result of natural variations attributed to atmospheric circulation variability rather than increase in local river runoff.

[5] The main goal of this paper is to describe the long-term and interannual variability in the summer FWC of the eastern Siberian shelf. In particular, we extend the analysis of *Steele and Ermold* [2004] and *Dmitrenko et al.* [2005], by quantifying the range of FWC anomalies (FWCA) on the East Siberian and Laptev sea shelves, and the relative importance of wind-forcing and climate on these changes. To this end, we use historical hydrographic summer data for the time period 1920–2005 to investigate the exchange of fresh water from the shelves to the Arctic Ocean and the pathways between various sub-regions of the Laptev and East Siberian seas. The domain of interest (see also Figure 1 and Table 1) is 1,187,500 km^2, and receives on average 728 km^3 of fresh water from river runoff each summer.

[6] The paper is structured as follows: section 2 gives a brief description of the data used in this study. The method used to analyze the data is presented in section 3. In section 4 we examine the time series of annual summer salinity and FWCA constructed by integrating the salinity anomalies over the entire Laptev and East Siberian sea shelves. In section 5 we discuss the effect of wind-forcing on the fraction of the FWCA on the shelves. Section 6 examines the time series of salinity and FWCA in the context of

Table 1. Main Geographical Characteristics of the Laptev and East Siberian Seas and Their Eight Sub-regions as Shown in Figure 1

Sea	Laptev Sea				East Siberian Sea			
Sub-region	1	2	3	4	5	6	7	8
Volume[a], km^3	5405	2645	5363	2657	5470	3073	5197	5380
Area[a], 10^3 km^2	100	120	117.5	157.5	165	202.5	122.5	202.5
Total	16,070 km^3 and 495,000 km^2				19,120 km^3 and 692,500 km^2			
Climatological mean summer salinity	31.64	26.65	29.82	19.68	27.92	21.42	29.57	27.34
Summer salinity standard deviation	1.15	1.27	1.43	1.68	2.03	2.47	1.16	2.84
Climatological mean summer river discharge, km^3	–	104	–	483	–	48	–	93

[a]Volume and area calculations based on the International Bathymetric Chart of the Arctic Ocean (IBCAO), 2001 version. Volume of every sub-region was calculated from surface to 70-m depth (or to the bottom if shallower).

climatic changes that have occurred in the Arctic over the last 60 years. Section 7 combines our inferences and discusses some aspects of as-yet-undetermined interplay between atmospheric circulation, river runoff, ice-related processes, precipitation, and evaporation to further our understanding of FWC variability.

2. Data

[7] We use the Arctic and Antarctic Research Institute (AARI) hydrographic data set which consists of summer (June–September) ship-based temperature and salinity observations (from 7101 and 4259 stations for the Laptev and East Siberian seas, respectively) collected in the ice-free regions of the Laptev and East Siberian seas in 1920–2005 (see Figure 1 for spatial and temporal coverage). In most cases, the ship-based surveys were done once per "hydrographic summer" season during the month of June through September. Prior to 1993, Nansen bottles were used, while in recent years, the data come from CTD measurements. We argue that the data set used in this study is far more comprehensive than either that of *Steele and Ermold* [2004] (who have used 1456 stations of a 2141-station data set by *Conkright et al.* [2002]), or that of the *Climatic Atlas of the Arctic Seas* [2004] (3150 stations for the Laptev Sea, and none for the East Siberian Sea).

[8] During the 58-year time period of observations in the Laptev Sea (1947–2005), an average of 103 stations were carried out each year. For the 48-year time period of observations in the East Siberian Sea (1947–1995), 81 stations were annually occupied. These stations occupied approximately 62% and 29% of the total area covered by the Laptev Sea and East Siberian Sea, respectively. In the Laptev Sea the two years with the largest number of stations occurred in 1961 (278 stations) and 1985 (243 stations) when 96% and 99% of the entire Laptev Sea surface was covered. In the East Siberian Sea the largest number of stations made was in 1964 when 298 stations covered 90% of the total sea-surface area. From the entire time series (1920–2005), there are 23 and 19 years of missing data in the Laptev and East Siberian seas, respectively. While the Laptev Sea hydrographic measurements cover almost the entire period from 1947 to 2005, measurements in the East Siberian Sea are only considered representative for a continuous time series starting in 1946 and ending in 1981. The distribution of stations in eight sub-regions of the Laptev and East-Siberian seas is shown on Figure 1 (bottom).

[9] The time series of summer (June–September) and winter (October–April) mean surface air temperature (SAT) and atmospheric pressure (SLP) were calculated from the National Centers for Environmental Prediction (NCEP–1948–2005 time period) data by averaging over the Laptev and East Siberian seas regions (Figure 1). The summer (June–September) mean SLP data are used to calculate the vorticity of the atmosphere over the same region. The horizontal resolution of the NCEP-derived data is 2.5° of latitude. The data sets of monthly mean land surface air temperature are from the Russian coastal stations (Figure 1) compiled by *Polyakov et al.* [2003a].

[10] August sea ice extent (1900–2000) over the Laptev and East Siberian seas as well as the time series of May fast ice thickness (1936–2000) at two coastal locations (station Sannikova in the eastern Laptev Sea, and station Chetirekh-stolbovoy in the East Siberian Sea, Figure 1) were obtained from *Polyakov et al.* [2003b]. Monthly mean river discharge data were taken from the Arctic-RIMS (Regional Integrated Monitoring System, http://rims.unh.edu) data set. In this data set, only data from rivers with runoff exceeding 20 km^3 for the whole hydrological summer (defined as the months between river ice break up and freezeup, May–September) were taken into account. Bottom topography was derived from the International Bathymetric Chart of the Arctic Ocean (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html).

3. Methods

[11] The 1920–2005 time series of annual summer mean salinity and FWCA for the Laptev and East Siberian seas (and sub-regions as defined in Figure 1) are calculated by integrating the annual summer salinity field over both depth and surface area. This approach was motivated by the fact that significant differences between the spatial patterns of surface and vertically integrated long-term mean standard deviations in the salinity field were observed (compare top and bottom panels in Figure 2, left). It is these differences in the vertical distribution of fresh water that led us to believe that the entire shelf hydrography may respond to wind-forcing rather than to inflow from river runoff as recently proposed by *Dmitrenko et al.* [2005]. While the atmospheric forcing mechanism considered here remains the same as by *Dmitrenko et al.* [2005], this study focuses on the salinity distribution with depth.

[12] Significant spatial variability in the salinity field over the Siberian shelf area (Figure 2), combined with different station locations, and data spatial and seasonal coverage from year to year, significantly complicates the interpretation of salinity time series. For these reasons, we pay particular attention to error estimates associated with the extrapolation of the spatially limited hydrographic data to the entire sea volumes. In the following, we also briefly describe the smoothing procedure, as well as uncertainties associated with linear trend calculations.

[13] The salinity measurements in the upper 70 m layer were used to calculate the time series of the mean summer salinity and FWC in the Laptev and East Siberian seas. We linearly interpolated the snapshot salinity measurements within a 150 km search radius onto a regular grid with 50 km and 1 m horizontal and vertical resolution, respectively. We experimented with various horizontal grid resolutions and search radii (20 to 150 km and 35 to 300 km, respectively), and found that these parameters best resolve the spatial variability while minimizing the smoothing associated with the averaging process.

[14] The climatological summer mean salinity was calculated over the period of 1920–2005 at each node of the regular 50 km grid where data were present. The climatological summer mean salinity for a given sea (S_0) was then calculated by averaging the individual station data over the total sea volume V_0 (see Table 1). For each particular summer, the mean salinity S_i of a sub-sea volume V_i where data are present was calculated along with climatological summer mean salinity S_c for the same volume. Finally, the annual mean salinity S of volume V_0 was estimated as the

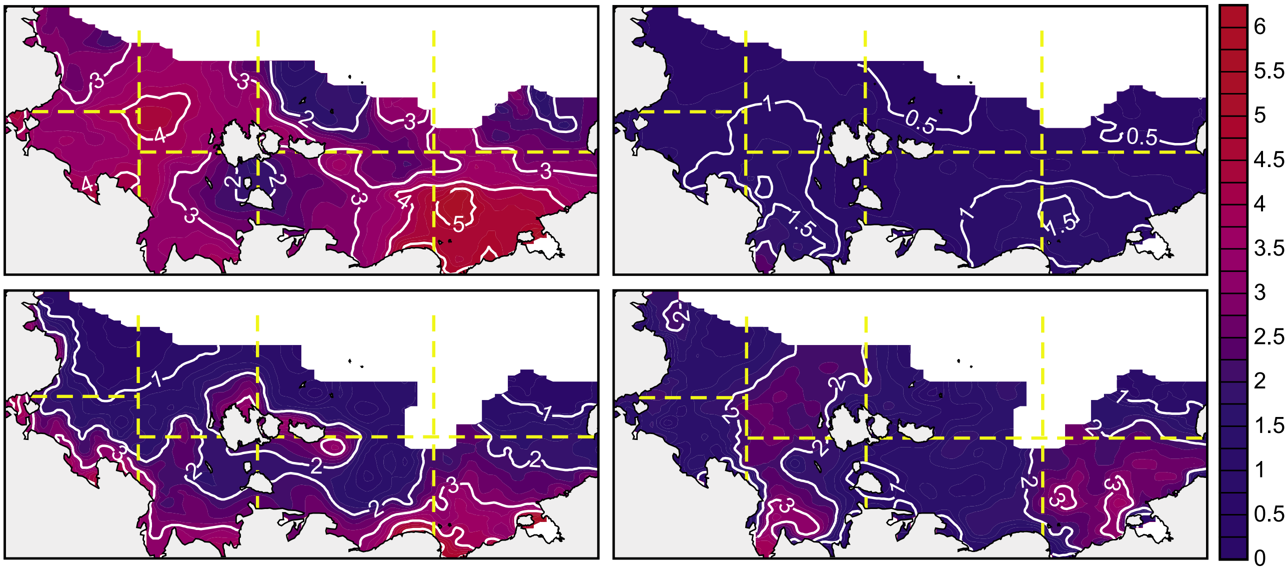

Figure 2. Surface (top) and vertically averaged (bottom) salinity standard deviations for summer (left) and winter (right, shown only for comparison). Yellow dashed lines show the eight sub-regions defined in Figure 1.

sum of S_0 and a correction δ calculated from the salinity anomaly $S_i - S_c$:

$$\begin{aligned} S &= S_0 + \delta \\ \delta &= S_i - S_c \end{aligned} \tag{1}$$

[15] The annual mean FWCA of volume V_0 was calculated using a modified version of the *Steiner et al.* [2004] relationship:

$$FWCA = \left(\int_{V_i(x,y,z)} \frac{S_c - S_i}{S_c} \mathrm{d}V \right) \cdot \frac{V_0}{V_i} \tag{2}$$

In the equation above, the ratio V_0/V_i is introduced to scale the FWC anomaly calculated in the volume V_i to that of the entire volume $V_{0,}$ assuming that the entire sea exhibits the same FWC variability as any of its sub-regions.

[16] To examine the salinity and FWCA error due to the scarcity in data coverage we calculate the summer mean salinity of 5000 random sub-domains covering 0 to 100% of the total sea volume for years when the station data cover the entire sea. These years include 1952–1956, 1960, 1961, 1964, 1967, 1968, 1970, 1977, 1980, 1985, and 1993 in the Laptev Sea and 1958, 1964, 1968, and 1977 in the East Siberian Sea (Figure 1, bottom). The salinities and FWCAs of the 5000 randomly selected sub-domains were calculated using equations (1) and (2). These sub-domain values were then compared with the "true" annual salinity and FWCA calculated from the salinity data for the entire sea volume. From the variance in salinity and FWCA calculated from the difference between the true and the sub-sampled values, we derive an estimate of the 95% confidence level for the entire region. Figure 3 shows the FWCA as a function of surface area coverage for the Laptev Sea. The total salinity and FWCA errors are defined as the sum of the error associated with the scarcity in data coverage (scaling error) and that associated with the standard error in measuring salinity.

[17] The time series of S (not shown) and FWCA for the eight sub-regions of the Laptev and East Siberian seas were constructed using the same technique. In this calculation however, a search radius of 50 km was used.

[18] While the scaling of the salinity time series from the volume V_i to the entire sea volume V_0 decreased the standard deviation by a factor of 3.7 and 2.4 for the Laptev and East Siberian seas, respectively (Figure 4), the standard deviation of the scaled FWCA time series increased by a factor of 1.1 and 5.8 for the Laptev and East Siberian seas, respectively (Figure 5). The standard deviation of the scaled FWCA time series for the Laptev and East Siberian seas is 356 and 1350 km^3, respectively. This is of the same order of magnitude as the error in summer mean FCWA (631 and 1091 km^3 for the Laptev and East Siberian seas, respectively).

[19] A 7-year running mean was applied to the FWCA time series to filter the noise associated with the limited data coverage and the errors attributed to the scaling procedure. The conclusions presented hereafter focus mainly on lower-frequency variability and are insensitive to the exact number of years used in the running average. We have, nevertheless, eliminated the years with insufficient spatial data coverage (Figures 4 and 5) in order to minimize the error in the linear trend estimates for the salinity and FWCA. To determine the minimum data coverage required for trend estimations, we examined the difference between the summer mean FWCA calculated by integrating over the entire sea volume, and the FWCA derived from summing the FWCA for each of the four sub-regions of the Laptev and East Siberian seas. Results show that the mean difference over the 85 year time series and the standard deviation of the difference between the two estimates are small only when years with

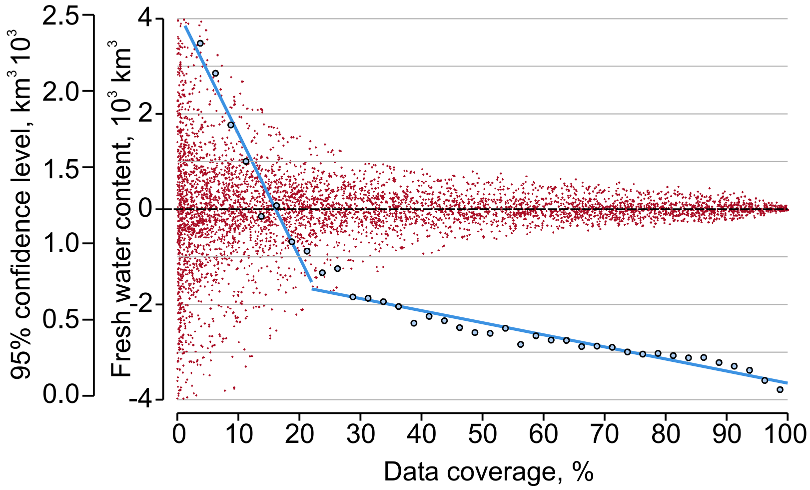

Figure 3. Error estimates associated with scaling of the fresh water content anomaly (FWCA) calculated from the limited data-covered domain to the entire Laptev Sea volume. Red dots show the FWCA computed for 5000 randomly chosen sub-domains with degraded spatial data coverage (see text for more detailed explanation). Blue dots indicate the 95% confidence level. The linear approximation of the 95% confidence level is indicated with a blue line.

all four sub-regions of the Laptev Sea and at least two sub-regions of the East Siberian Sea are included. The years that did not meet this criterion were eliminated from the trend estimations (see Figures 1, 4, and 5).

4. Salinity and Fresh Water Content Anomaly Long-Term and Interannual Variability

[20] Here we examine the variability and trend of the salinity and FWCA time series for the Laptev and East Siberian seas, and for each of the eight sub-regions shown in Figure 1. In addition, we try to identify the sub-regions that control the interannual variability of a given sea, by examining the interconnection between the sub-regions that display the largest summer mean salinity interannual variability (Figure 2, bottom left) that correlates with that of the total volume.

[21] The 7-year running mean of summer mean salinity shows relatively large interannual variability, with standard deviations of 0.55 and 0.76 psu for the Laptev and East Siberian seas, respectively (Figures 6 and 7). The corresponding standard deviations of FWCA are 360 and 563 km^3. For reference, the long-term summer mean Lena River discharge (not shown) into the Laptev Sea is 458 km^3, and its standard deviation is equal to 56 km^3.

[22] The 7-year running mean salinity and FWCA in the Laptev Sea display a quasi-decadal 10–15-year periodicity that is persistent over the entire period of continued observations (1950s to 2000s, Figure 6). In the East Siberian Sea the same periodicity is observed for the 1950–1980 time period when the spatial data coverage was larger than 20% (Figure 4, bottom panel and Figure 7). The amplitude of the quasi-decadal oscillation in the Laptev Sea (Figure 6) is approximately 600 km^3. This corresponds to a mean salinity change of 0.95 psu between the peaks and valleys. For the East Siberian Sea (Figure 7) the mean amplitude is approximately 1300 km^3. This corresponds to a 1.8 psu change in mean salinity.

[23] While the same quasi-decadal variability is present in all southern sub-regions (i.e., #2, 4, 6, and 8; see Figure 8), the period and phase are not the same. For instance, sub-region 4 has longer-term variability (with a general decline in the 50s and 60s and a general increase in the 80s and 90s) superimposed on a quasi-decadal periodicity. This leads to a poor correlation between sub-regions 2 and 4, even though the peaks and valleys in both time series are in phase. On the other hand, sub-regions 6 and 8 are highly correlated (0.68 and 0.70 for salinity and FWCA, respectively). These correlations (and others presented later) are statistically significant at the 95% confidence level. Among all four sub-regions of the Laptev Sea the only statistically significant correlation (0.67) is that between the FWCA time series for the entire Laptev Sea and for sub-region 4. Given that the highest salinity standard deviation is present in sub-region 4 (Table 1 and Figure 2, bottom left), one may speculate that sub-region 4 drives the interannual salinity and FWCA variations in the Laptev Sea. The interannual variability in salinity for sub-region 1 (not shown) follows that reported by *Swift et al.* [2005] for the adjacent Arctic Ocean.

[24] In the East Siberian Sea, sub-regions 6, 7, and 8 are correlated with one another (correlation coefficient ranging between 0.52 and 0.86), but before 1946, and from 1968 onward the data coverage of sub-region 7 is too sparse (Figure 1, bottom) to allow reliable conclusions to be drawn. We found relatively high correlations of 0.75 and 0.91 between the FWCA time series obtained for the entire East Siberian Sea with the FWCA for sub-regions 6 and 8, respectively. From this, and from the fact that the same two regions have the highest standard deviation in salinity (Table 1, and Figure 6 bottom left), we speculate that the interannual FWCA variability in the East Siberian Sea is mainly driven by the interannual variations of its southern sub-regions.

[25] The correlation between the 7-year running mean salinity and FWCA time series for the Laptev and East

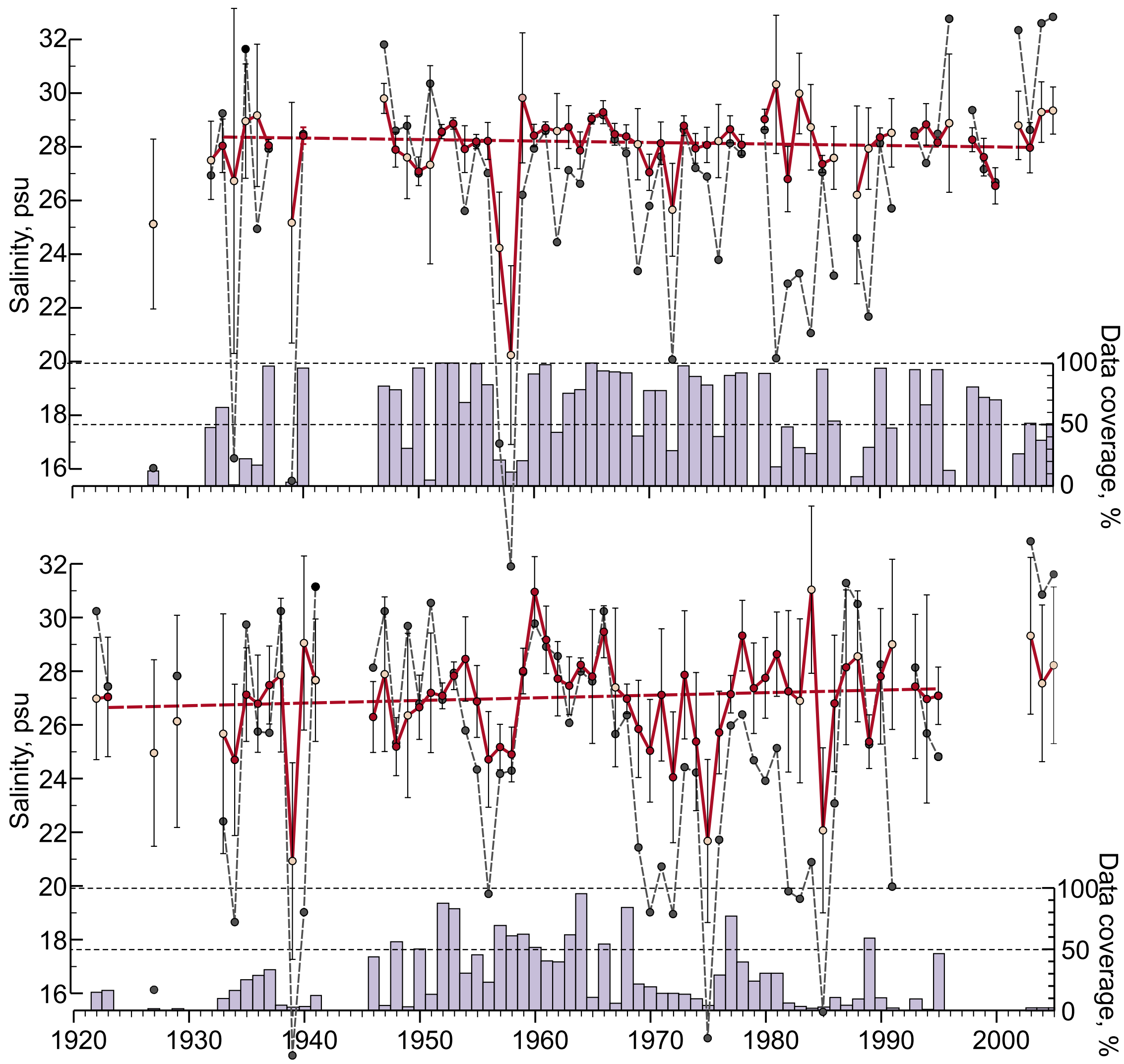

Figure 4. Time series of the summer annual mean salinity over the Laptev (top) and East Siberian (bottom) seas. Black dots show the annual mean salinity S_i obtained by integration over the data-covered volume V_i. Annual mean salinity S scaled to the entire sea volume V_0 is depicted by red and pink dots. The error bars show its statistical error defined as the sum of scaling error, which is due to limited data coverage, and the standard error calculated from the salinity measurements. The data coverage (%) is shown in the lower panels. Where the spatial coverage of the data is limited the error bars indicate the scaling error rather than the data standard error. Pink dots mark those years for which no data were derived to calculate the linear trend in salinity (red dashed line) due to insufficient spatial data coverage (see text for more detailed explanation).

Siberian seas over the periods of 1920–1954 and 1962–2005 are 0.66 and 0.59, respectively. Both correlation coefficients are significant above the 95% level. In 1957–1958 the low salinity value in the Laptev Sea (Figure 4, top) is due to the lower spatial data coverage (see Figure 1 bottom, and Figure 4 top). In fact, for those two years, only sub-region 4 has a significant amount of data coverage. This salinity minimum as well as others in late the 1930s, early to mid-1970s, and mid-1980s affect the 7-year running mean, lowering the correlations between salinity and FWCA time series for the Laptev and East Siberian seas down to 0.38 and 0.32, respectively.

[26] For the Laptev Sea, the linear trends in the salinity and FWCA time series are not statistically significant and are equal to −0.06 psu/decade and 58 km^3/decade, respectively (Figures 4 and 5, top). This corresponds to a 0.38 psu decrease in mean salinity and 400 km^3 in FWC gain for the entire 70-year time period (1933–2003). Over the East Siberian Sea (Figures 4 and 5, bottom) the opposite (not statistically significant) tendency was observed: i.e., a positive trend in mean salinity of 0.10 psu/decade and a corresponding fresh water loss of 79 km^3/decade. For the period of 1923 to 1995 this corresponds to 0.7 psu of salinity rise and 568 km^3 of fresh water loss.

[27] The same tendencies are evident from the analysis of regional salinity and FWCA patterns (Figure 8). As for the analysis of the Laptev and East Siberian seas, the sub-

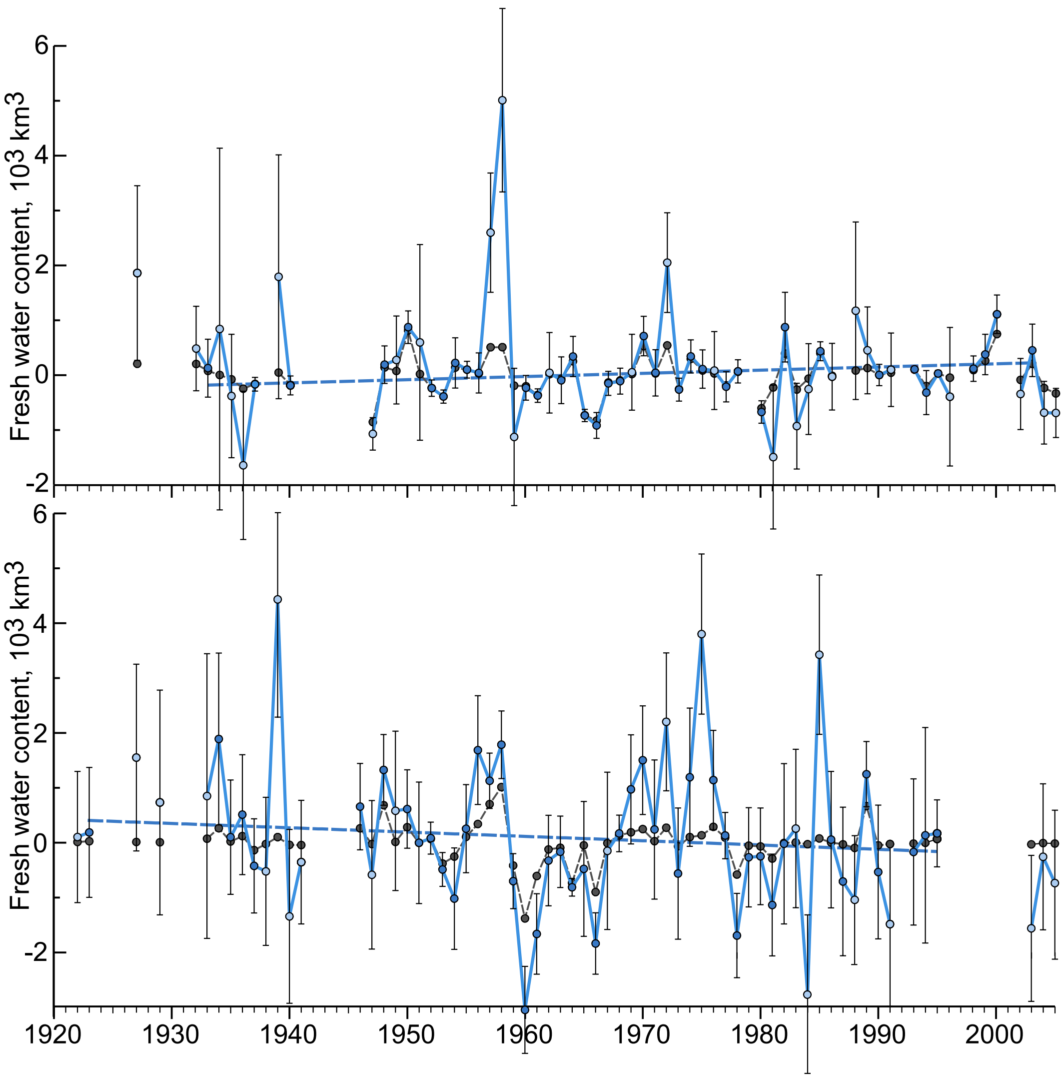

Figure 5. Time series of the summer fresh water content anomalies (FWCA) over the Laptev (top) and East Siberian (bottom) seas. Black dots show the annual mean FWCA obtained by integrating over the volume V_i covered by data. The annual mean FWCA scaled to the entire sea volume V_0 is shown by blue dots. Error bars show its statistical error as in Figure 4. Light blue dots mark those years for which no data were derived to calculate the FWCA linear trend (blue dashed line) due to insufficient spatial data coverage (see text for more detailed explanation).

regional trends are not statistically significant. Among the four sub-regions of the Laptev Sea, only the northwestern sub-region 1 shows a fresh water loss of 17 km^3/decade (Figure 8, left top), while the three other sub-regions gain freshwater at a rate of 29 km^3/decade. Note that for the period of 1933–2003 the positive balance of 84 km^3 between all four sub-regions of the Laptev Sea is almost 5 times smaller than the estimate derived for the Laptev Sea as a whole (400 km^3). All four sub-regions of the East Siberian Sea show a combined loss of fresh water (Figure 8, right) equal to 200 km^3/decade. This is significantly larger than our estimate for the East Siberian Sea as a whole (79 km^3/decade). We attribute the large discrepancy between the sub-regional and regional analysis to errors in the statistically insignificant linear regression of scaled (sometimes sparse) data for both sub-regional and bulk calculations. Obviously, only the qualitative tendencies revealed from this analysis are considered reliable.

5. Wind-Driven Interannual Variability of the Eastern Siberian Shelf Fresh Water Content

[28] In order to better understand the interannual variability of the eastern Siberian shelf summer hydrography, we analyze filtered salinity and FWCA time series for the Laptev and East Siberian seas. In particular we examine their interannual variations and how they relate to summer mean atmospheric circulation, river discharge, summer ice extent over the eastern Siberian shelf, and summer mean surface and sea level air temperature. We will show that the quasi-decadal periodicity found in the FWCA and salinity time series is mainly caused by the variability in atmospheric forcing.

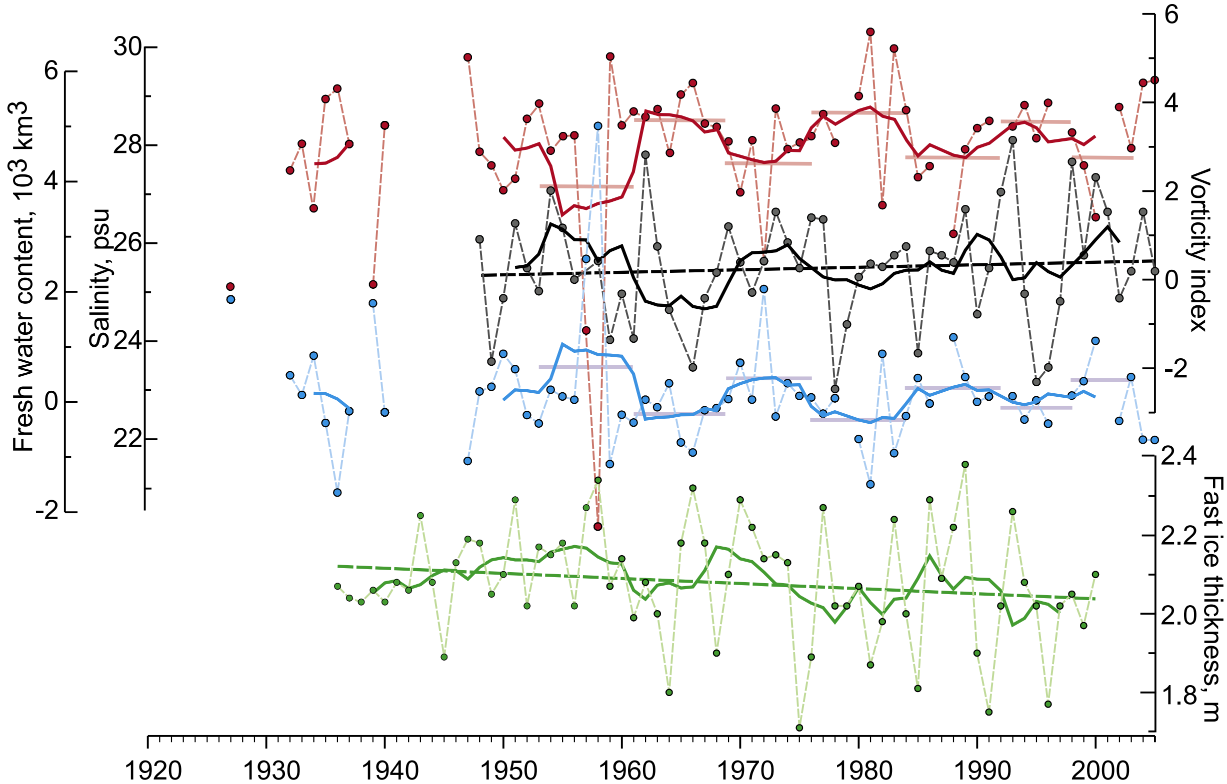

Figure 6. The 7-year running mean of the Laptev Sea annual summer mean salinity *S* (red dots) and FWC anomaly (blue dots) shown by red and blue solid lines, respectively. Horizontal lines show quasi-decadal 10–15 year mean salinity (pink), FWC (violet), and atmospheric vorticity (gray). The black line shows the 7-year running mean of the annual summer atmospheric vorticity depicted by gray dots. The 7-year running mean of the May fast ice thickness (green dots) at station Sannikova (Laptev Sea) is shown by a green line. The linear trends are shown by bold dashed lines.

[29] The shallow Siberian shelf is believed to be sensitive to wind-forcing. The position of the zero vorticity contour, which separates two predominant large-scale centers of atmospheric circulation over the Arctic Ocean, oscillates between the Laptev and East Siberian seas [*Johnson and Polyakov*, 2001]. This unique position of the Laptev and East Siberian sea shelves and the associated SLP centers renders their surface hydrography very sensitive to the shifts between predominantly positive (cyclonic) and negative (anti-cyclonic) atmospheric vorticity [*Dmitrenko et al.*, 2005]. *Polyakov and Johnson* [2000], *Johnson and Polyakov* [2001], and *Steele and Ermold* [2004] all reported a relationship between decadal variability in sea surface salinity anomalies on the Siberian shelf and the Arctic or North Atlantic Oscillation (AO - NAO)–two atmospheric circulation indices that are closely related to the extent to which storms penetrate into the eastern Arctic. From these considerations, we hypothesize that atmospheric circulation drives not only the interannual variability in the sea surface salinity, as reported by *Dmitrenko et al.* [2005], but also the entire shelf water column.

[30] We use a vorticity index to characterize the atmospheric circulation and to compare it with composite salinity and FWC anomaly time series. The vorticity index gives both the sign and magnitude of atmospheric vorticity, and was first proposed by *Walsh et al.* [1996]. It is defined as the numerator of the finite difference Laplacian of SLP for an area within a radius of 550 km of 85°N and 125°E, a region located in the Arctic Ocean close to the northeastern Laptev Sea. A negative vorticity index corresponds to an anticyclonic atmospheric circulation, and a positive index, to a cyclonic circulation. Summer (June-September) mean vorticity indices were derived from monthly SLP NCEP data. When the vorticity is negative, winds generally blow northward (offshore) in the Laptev Sea and westward (along-shore) over the East Siberian Sea. When the vorticity is positive winds blow eastward (along-shore) over the entire Laptev and the western East Siberian seas. This is the prevailing mode of atmospheric circulation in the summer in this region.

[31] Figures 6 and 7 show the summer mean salinity and FWCA together with the summer mean atmospheric vorticity. The 7-year running mean vorticity index exhibits quasi-decadal variability. Before 1982, the vorticity anomaly variations (relative to the long-term trend) demonstrate truly positive (cyclonic) and negative (anticyclonic) vorticity index values. After 1982 the vorticity index remains positive on average, but still maintains quasi-decadal periodicity (Figures 6 and 7). The 7-year running mean vorticity index is highly correlated with FWCA (0.74) and salinity anomalies (−0.68) for the entire Laptev Sea (see Figure 6). For the 1948–1985 time period when the spatial and temporal data coverage is most complete (c.f. Figures 1 and 4) the correlation is even higher (0.80 and −0.77,

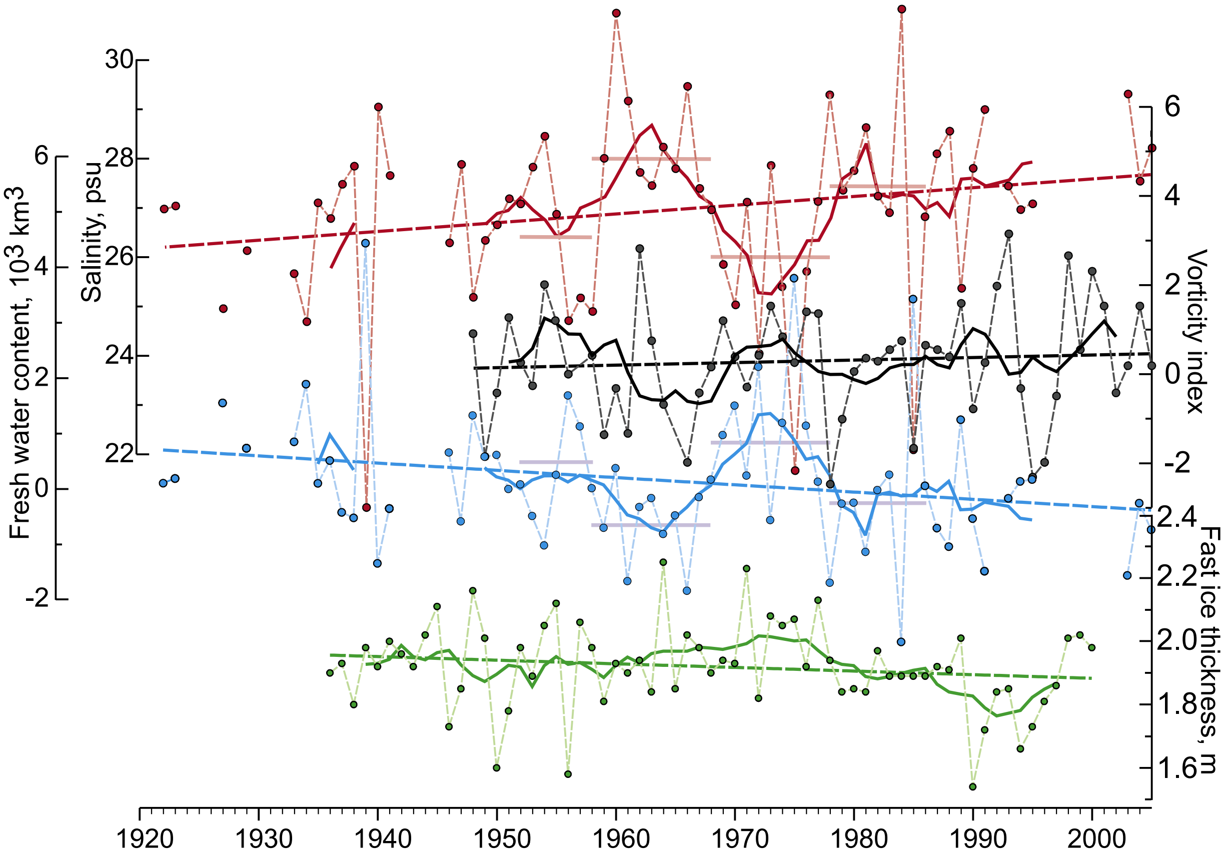

Figure 7. The 7-year running mean of the East Siberian Sea annual summer mean salinity *S* (red dots) and FWC anomaly (blue dots) shown by red and blue solid lines, respectively. Horizontal lines show quasi-decadal 10–15-year mean salinity (pink), FWC (violet), and atmospheric vorticity (gray). Black line shows the 7-year running mean of the annual summer atmospheric vorticity depicted by gray dots. The 7-year running mean of the May fast ice thickness (green dots) at station Chetirekhstolbovoy (East Siberian Sea) is shown by green line. The linear trends are shown by bold dashed lines.

respectively). While the correlation is lower for the East Siberian Sea (0.47 for FWCA and −0.49 for salinity anomalies: Figure 7), it is still statistically significant. Again, when only the years with good spatial data coverage (1948–1981) are considered, the correlation coefficients are higher (0.59 and −0.60). Of particular interest is the reduction in the amplitude of the quasi-decadal salinity and FWCA oscillations that are consistent with the decreasing amplitude of the quasi-decadal vorticity oscillations (Figures 6 and 7). Moreover, the positive values of the 7-year running mean vorticity, observed since 1982, are accompanied by a substantial reduction in the quasi-decadal salinity and FWCA variability in the Laptev Sea (Figure 6). Note that because the data are scarce (Figures 1 and 4, bottom), the quasi-decadal periodic disruption in the East Siberian Sea since the 1980s cannot be clearly identified (Figure 7).

[32] For the entire sea volumes of the Laptev and East Siberian seas there were no statistically significant correlations between the FWC and salinity anomalies and the 7-year running mean time series of summer ice extent, summer SAT, AO/NAO indices, and summer mean river discharge. On the basis of the simplest linear regression model, the atmospheric vorticity explains approximately 55 and 22 % of the FWCA interannual variability for the Laptev and East Siberian seas, respectively. It corresponds to a FWCA standard deviation of 277 and 262 km^3 for the Laptev and East Siberian seas. The FWCA residual exhibits no correlations with any of the time series mentioned above. In the Laptev Sea the mean FWCA for the positive atmospheric vorticity anomaly differs from that of the negative atmospheric vorticity anomaly by 313 km^3. For the East Siberian Sea the difference is slightly less (296 km^3). Note that the long-term summer mean river runoff is approximately 587 and 141 km^3 for the Laptev and East Siberian seas, respectively (Table 1). The long-term summer mean meltwater influx into the Laptev and East Siberian seas is approximately 449 km^3 and 529 km^3, as estimated by *S. Shutilin* [pers.com.] using a sea-ice dynamic-thermodynamic model by *Makshtas et al.* [2003].

[33] The regional patterns of correlation between summer hydrography and atmospheric vorticity are of particular interest. Among all four sub-regions of the Laptev Sea only sub-region 4 has statistically significant correlation coefficients of 0.76 (FWCA) and −0.72 (salinity) for the entire period of observations. The variability of atmospheric circulation explains about 58% (120 km^3) of the FWCA interannual variations. Of particular interest is the statistically significant correlation between the FWCA residual and the August ice extent (−0.52) and SAT at the coastal

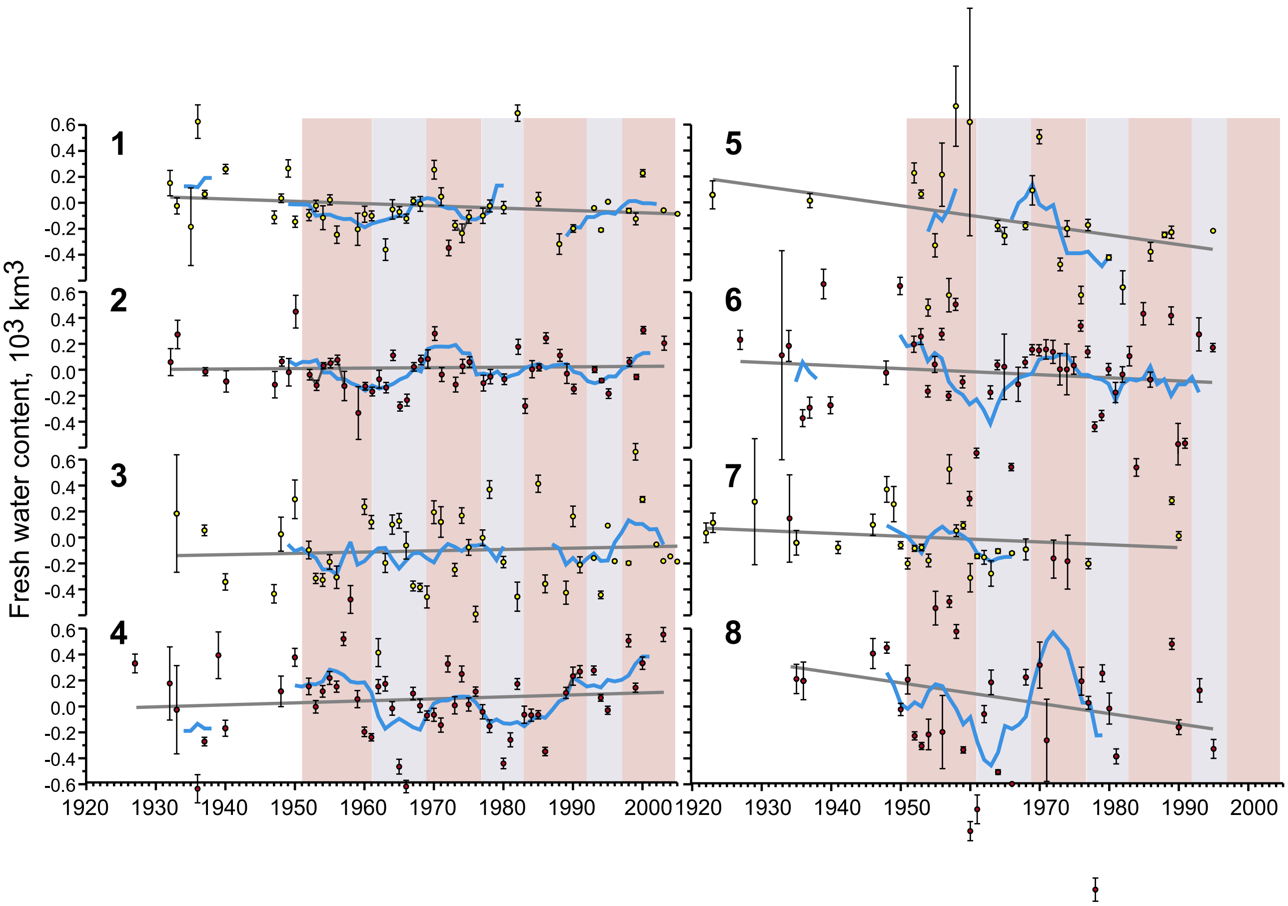

Figure 8. The 7-year running mean of the annual summer fresh water content anomaly (FWCA) (red and yellow dots) integrated over the eight sub-regions of the Laptev (left) and East Siberian (right) seas are shown by blue lines. Error bars indicate the FWCA statistical error as in Figure 5. The linear trend is shown by gray lines. Pink and blue shading indicates years with 7-year running mean positive and negative anomalies in atmospheric vorticity index, respectively.

station located at the mouth of the Lena Delta (0.49). This suggests that meltwater from sea ice may explain a smaller, but still significant fraction of the variance in FWCA. There were no statistically significant correlations of the FWCA residual with other time series, particularly with the Lena River discharge. The correlation between the atmospheric vorticity and the FWCA for sub-region 2 is slightly below the level of significance for the entire period of available data. The correlation for the shorter time period from 1957–2001 however is significant. Surprisingly, our analysis did not reveal significant correlations between the Lena River discharge and the salinity or FWCA in any of the four sub-regions in the Laptev Sea. We infer from this that Lena river fresh water are just in transit in the Laptev Sea and that riverine outflow from the Laptev Sea is significant. Among all other variables, the only significant correlation was found between the salinity and FWCA in sub-region 1, and SAT derived from NCEP data and integrated over the entire Laptev Sea area. However, the poor correlation with regional SAT data over the same region (see Figure 1 for position of SAT regional observations) does not support this relationship.

[34] Among the four sub-regions of the East Siberian Sea, only sub-regions 7 and 8 have significant correlations with atmospheric vorticity of 0.80 and 0.64 for the FWCA, and −0.79 and −0.68 for salinity, respectively. In these sub-regions, the variability in atmospheric circulation explains 63% and 42% of the FWCA interannual variations, respectively, corresponding to 56 and 152 km^3 of fresh water content. Of all the other variables considered in this studies, the residual for sub-region 8 correlates only with the AO (0.55) and NAO (0.77) indices. For sub-region 7, the residual correlates only with the NAO index (0.84). Overall, this shows an impact of the global atmospheric circulation on the eastern Arctic hydrography. The correlation between atmospheric vorticity and sub-region 6 FWCA (0.42) is slightly lower than the 95% level of confidence. However, the high correlation with NCEP SLP data (−0.66) clearly indicates that sub-region 6 is also driven by atmospheric circulation. Of all the other variables that we examined, the only statistically significant relationship found was between the East Siberian Sea August ice extent and FWCA for northern sub-regions 5 and 7 (−0.50 and −0.62, respectively), again indicating the importance of sea-ice meltwater influx.

[35] Figure 9 shows the spatial distribution of the correlation between FWCA and atmospheric vorticity. These results are in general agreement with those from the sub-

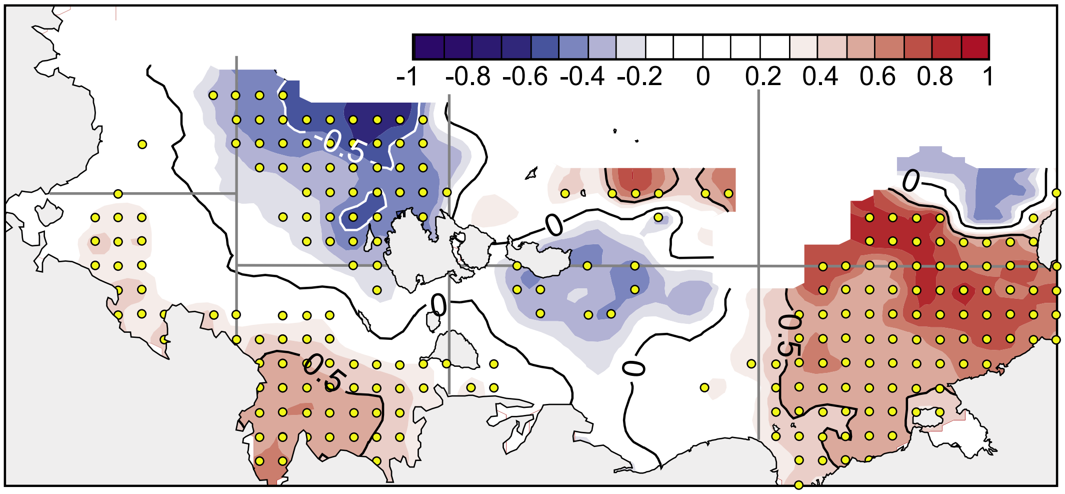

Figure 9. Correlation of annual summer FWCA with annual summer atmospheric vorticity index. No data restoring or smoothing were applied. Yellow dots mark statistically significant correlation (with 95% confidence).

regional analysis, except for the area of negative correlation in sub-region 3, which did not stand out in our sub-regional analysis. Note that when calculating individual correlations in the grid points of Figure 9 no data scaling or smoothing was applied.

[36] Summarizing our findings from the correlation and regression analysis, we conclude that the interannual variability of the FWCA for both the Laptev and East Siberian seas is mainly driven by atmospheric circulation. Positive FWCA is predominantly located in the southern Laptev and the eastern East Siberian seas, with fresher water during positive anomaly of atmospheric vorticity, and saltier water during negative vorticity anomaly (Figures 8 and 9). This is the main pattern that controls the entire fresh water content variability of the Laptev and East Siberian seas (Figures 6 and 7). Our results also indicate the pathways along which Laptev Sea fresh water is lost to the Arctic Ocean during negative vorticity anomalies, and to the East Siberian Sea during positive vorticity anomalies. When the detrended atmospheric circulation is antycyclonic, approximately 313 + 296 $\approx$ 600 km^3 of fresh water is lost by the eastern Siberian shelf at the expense of the Arctic Ocean (through the northeastern Laptev Sea, Figure 9). During a cyclonic circulation regime, this fresh water is equally redistributed between the Laptev and East Siberian sea shelves. This results in fresh water accumulation over the southeastern Laptev Sea shelf and the eastward diversion of river runoff toward the East Siberian Sea. From the data available, it is not possible to account for the fresh water lost via the Chukchi Sea and the adjacent Arctic Ocean. In terms of FWC variability, the difference between positive and negative phases of atmospheric vorticity anomaly is striking. In fact, 500–600 km^3 of fresh water is redistributed either in the Arctic Ocean or the eastern Siberian shelf. This amounts to approximately 70–80% of the total fresh water influx from river runoff into the Laptev and East Siberian seas. It also represents 60–70% of the fresh water stored in the Laptev Sea winter ice cover. The trend toward more positive atmospheric vorticity values since 1982 does not disrupt the wind-driven quasi-decadal salinity and FWC variability in the Laptev Sea. However, it does reduce its amplitude.

6. The Long-Term Variability of Summer Fresh Water Content: Implication for Climatic Change

[37] In this section we discuss the results in the context of the climatic changes that have occurred in the Arctic over the last 50–60 years. We pose the following question: Can we detect a climate change signal (associated with changes in melting/freezing along the shelf, and in river runoff) in the eastern Siberian shelf hydrography given that the variability in atmospheric forcing dominates the shelf fresh water budget? Alternatively, can we attribute the long-term variability of atmospheric vorticity to climate change? The amount of and variation in Arctic river discharge is generally believed to be critically important for the Arctic Ocean surface salinity and sea ice formation, and may also have an impact on the global ocean thermohaline circulation [*Aagaard and Carmack*, 1989; *Peterson et al.*, 2006; *Serreze et al.*, 2006]. The annual discharge from the six largest Eurasian Arctic rivers (Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina) shows a positive trend of 2.0 ± 0.7 km^3/a for the 1930–2000 time period. In 1999 the annual mean discharge was approximately 128 km^3 larger than discharge in the 1930s [*Peterson et al.*, 2002]. This, together with the fresh water influx associated with the decline of sea ice extent and thickness observed in the last few decades [*Laxon et al.*, 2003; *Rigor and Wallace*, 2004; *Stroeve et al.*, 2005] could shift the Arctic Ocean toward a generally fresher state [*Peterson et al.*, 2006]. Instead, *Steele and Ermold* [2004] and *Swift et al.* [2005] reported a tendency toward saltier surface waters in the Arctic Ocean and the Siberian shelf. This is also confirmed by numerical modeling results [*Häkkinen and Proshutinsky*, 2004; *Bitz et al.*, 2006]. In fact, *Bitz et al.* [2006] suggested that sea ice decline results in increased growth the following winter due to the thinner (less insulating) ice on the shelf, and increased salinity of surface waters.

[38] Our results based on a comprehensive hydrographic data set do not reveal statistically significant trends of salinity and FWCA over the eastern Siberian shelf (Figures 4 and 5). In the East Siberian Sea the rate of increase in salinity (0.10 psu/decade) is about 8 times lower than estimates by *Steele and Ermold* [2004] based on a less extensive data set. The spatial pattern of sea surface salinity anomaly in all four sub-regions of the East Siberian Sea, however (Figure 8, right), is consistent with that proposed by *Steele and Ermold* [2004]. In the Laptev Sea, the opposite tendency is observed with a freshening of −0.06 psu/decade. This signal is dominated by the freshening of the eastern Laptev Sea (Figure 8, left bottom). In the southwestern Laptev Sea, the ocean salinities remain approximately the same. In the northwestern Laptev Sea (Figure 8, left top) the positive salinity trend is in good agreement with results reported by *Swift et al.* [2005] for the adjacent Arctic Ocean, and is also in qualitative agreement with results by *Steele and Ermold* [2004].

[39] At first glance, the positive (although not statistically significant) salinity trend in the entire East Siberian and northwestern Laptev seas appears to contradict with the summer ice decline over the outer shelf of the Laptev and East Siberian seas [*Rigor and Wallace*, 2004], and the increase of fresh water influx with increasing river discharge [*Peterson et al.*, 2002]. A positive salinity trend is, however, consistent with the modeling results of *Bitz et al.* [2006] which indicate that the surface layer fresh water balance is dominated by increased salt release associated with increased ice formation the following winter rather than by increased melting of sea ice. The positive statistically significant relationship between ice retreat and FWCA in the northern sub-regions of the East Siberian Sea, however, is definitely attributed to the fresh water influx from sea ice melting at the ice edge; the ice edge at the end of summer is usually located in or near those sub-regions [*Rigor and Wallace*, 2004]. Thus a strong retreat of the summer sea ice extent is expected to result in a large input of meltwater to the northern part of the shelves. However, this positive relationship between ice retreat and FWCA seems not to be in conflict with results by *Bitz et al.* [2006]. The high salt flux caused by strong new ice production is a process that is most active during early winter. It is not clear (since the residence time of water on the shelf is not known) whether the brine enriched water masses could be traced on the shelf eight months later during the following summer as a remnant of this process.

[40] While the residence time of the meltwater and river discharge water on the eastern Siberian shelf remains poorly known, one may speculate that the fresh water outflow toward the Arctic Ocean exceeds the inflow from the ice melt and river water influx, or that more ice formation is present the following winter due to a thinner ice cover. As was shown in section 5, the atmospheric vorticity dominates the fresh water outflow from the east Siberian shelf, and a positive atmospheric vorticity anomaly results in a positive FWCA. Therefore the slightly positive vorticity trend (Figures 6 and 7) is more indicative of the inner shelf fresh water accumulation rather than of fresh water outflow to the Arctic Ocean.

[41] Apparently, an as-yet-undetermined interplay between atmospheric circulation, river runoff, and ice-related processes may explain the disagreement between the postulated increase of fresh water inflow and the decrease of fresh water storage over the eastern Siberian shelf. However, in the Laptev Sea we did not find a relationship between summer atmospheric vorticity and summer AO/NAO, SAT, ice extent, or river discharge. In the East Siberian Sea the summer atmospheric vorticity correlates only with ice extent (−0.48) and SAT (0.55). This does not allow us to draw firm conclusions, as these correlations are equally supportive of a wind-driven ice outflow hypothesis and a meltwater inflow hypothesis.

[42] From these results we conclude that the change in fresh water inflow associated with climate change is significantly smaller than that associated with natural wind-driven variability. The Lena River is the main source of fresh water input to the Laptev Sea. Since the mid 1930s the Lena River summer (May–September) discharge has increased only by 22.4 km^3 [*Yang et al.*, 2002] (compare this with the standard deviation of Lena River long-term mean summer discharge of 55.6 km^3). Over the same period of time however, subregion 4, which is adjacent to the Lena Delta (Figure 1 and Table 1), exhibits a clear increase in FWC (Figure 8, left bottom). This increase corresponds to a fresh water gain of 110 km^3 - an amount which greatly exceeds the river discharge increase reported by *Yang et al.* [2002]. For the entire Laptev Sea, the difference in FWC is approximately 400 km^3 (see section 4). This exceeds by a factor of almost 20 the net river discharge increase reported by *Yang et al.* [2002]. Although the positive tendency of the Laptev Sea FWC is consistent with the increase in river discharge, the effect of river discharge is unclear, particularly given the fact that the FWC wind-driven variability (500–600 km^3) is about 20–30 times larger. This conclusion is in agreement with results of the Kara Sea FWCA numerical modeling by *Harms and Karcher* [2005]. They found that the interannual variability of the river discharge is too low to explain the observed hydrographic changes.

[43] *Polyakov et al.* [2003b] reported that the long-term (1936–2000) ice extent trends in the Laptev and the East Siberian seas are small and not statistically significant, while trends derived from shorter-term records are not indicative of the long-term tendencies due to large-amplitude low frequency variability. Between the 1920s–2000s the long-term tendency of ice decline, totaling 50 and 70 km^2 in the Laptev and East Siberian seas, respectively, provides a negligible amount of the additional fresh water inflow. Furthermore, over recent decades the trend in sea-ice decline in the Laptev Sea has remained constant [*Polyakov et al.*, 2003b; *Rigor and Wallace*, 2004]. This is consistent with the tendency toward more positive FWC in subregion 4. While precipitation and evaporation were not part of our analysis, we believe that their contribution is also negligible. From 1979 to 2001 the annual mean difference between precipitation and evaporation over the entire Arctic Ocean shows no significant trend [*Serreze et al.*, 2006]; the standard deviation of this difference is reported to be on the order of 170 km^3 [*Serreze et al.*, 2006, Table 3].

[44] It is also clear that there is a significant amount of spatial variability over the Siberian shelf area, even on relatively small spatial scales; this variability combined with different station locations and data spatial coverage

from year to year, significantly complicates evaluation and further attribution of the long-term trends.

7. Conclusions and Final Remarks

[45] The purpose of this paper is to examine the mechanisms driving the long-term and interannual variability of the fresh water storage of the eastern Siberian shelf. We provide quantitative estimates of the contribution of all major factors affecting the shelf water hydrography. To this end, we analyze time series of summer annual FWC and vertically averaged salinity anomalies calculated from historical hydrographic records for the period of 1920s–2000s, for both the Laptev and East Siberian sea shelves.

[46] A careful consideration of the salinity and FWC anomaly time series indicates that noise associated with limited spatial and temporal data coverage dominates the annual data. However, the 7-year running mean FWC and salinity anomaly time series clearly show a quasi-decadal periodicity that is most pronounced during the time period of continuous comprehensive hydrographic measurements. A multiple regression between the FWC and salinity anomaly time series and time series of summer mean atmospheric vorticity, ice extent, SST/SAT, and AO/NAO indicates that the quasi-decadal periodicity is mainly controlled by the atmospheric vorticity. When the detrended summer mean atmospheric circulation is more anticyclonic (negative phase of the atmospheric vorticity anomaly), approximately 500–600 km^3 of fresh water is lost from the eastern Siberian shelf toward the Arctic Ocean, through the northeastern Laptev Sea. When the atmospheric circulation is cyclonic (positive vorticity anomaly), this fresh water is redistributed almost equally between the southern Laptev and East Siberian sea shelves.

[47] This wind-driven FWCA (of 500–600 km^3) represents about 35% of the total fresh water inflow provided by river discharge and melting ice. The interannual variability in atmospheric forcing, combined with the sparseness of the data during certain periods of time, makes it difficult to identify the long-term tendency of fresh water storage that may be attributed to climate change. The long-term trends of salinity and FWC anomalies were not statistically significant for either the Laptev or the East Siberian seas. The fresh water lost from the East Siberian Sea is consistent with results reported by *Steele and Ermold* [2004]. In the Laptev Sea the fresh water gain is in qualitative agreement with a long-term increase in river discharge. However, a clear attribution remains difficult due to a relatively small trend compared to a large interannual variability.

[48] Presumably, an interplay between atmospheric circulation, river runoff, ice-related processes, precipitation, and evaporation that is not yet well understood may explain the portion of the variability in salinity and FWC that is not related to local atmospheric patterns. Here the interplay between summer and winter processes (which was not part of our analysis) is of particular interest. Specifically, a matter of debate is the positive correlation of 0.62 between the summer 7-year running mean FWCA and the winter land-fast ice thickness in the Laptev Sea (Figure 6, bottom; see also Figure 1 for the locations of fast ice measurement). In the East Siberian Sea the correlation of 0.43 is slightly below the level of confidence. Moreover, for both the Laptev and East Siberian seas, the correlation coefficient between fast ice thickness and winter SAT NCEP data are −0.54 and −0.60 (statistically significant at the 95% level of confidence). This indicates that interannual variation of land-fast sea-ice thickness is due to thermodynamic factors. One might link the FWCA to the land-fast ice thickness through the additional fresh water influx that results from the melting of thicker ice the following summer. However, the fresh water stored in the fast ice is taken away from the ocean during winter and returned to the ocean the following summer, and therefore cannot explain the FWCA interannual variations directly if one assumes that the inner shelf water residence time is longer than one year. Again, an as-yet-undetermined interplay between summer and winter processes is taking place. Further analysis of seasonal variations in sea surface salinities and fresh water content will help us to answer this question. This is the goal of future work that we are presently undertaking.

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